Opportunities for Parton Saturation Physics at RHIC and LHC

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Outline

- Motivation
- Open questions at RHIC and LHC
- QCD at high energies – saturation physics
- Typical example - Hadron multiplicities in AA
- Opportunities for saturation physics at RHIC and LHC

WHERE ?

RHIC @ BNL

pp, dAu, AuAu and CuCu at $\sqrt{s} = 20...200\ AGeV$

RHIC II will improve detectors for rare processes and enhance statistics

LHC @ CERN

Will collide PbPb at $\sqrt{s} = 5500\ AGeV$ and also pPb or dPb (under discussion) at $\sqrt{s} = 8200\ GeV$

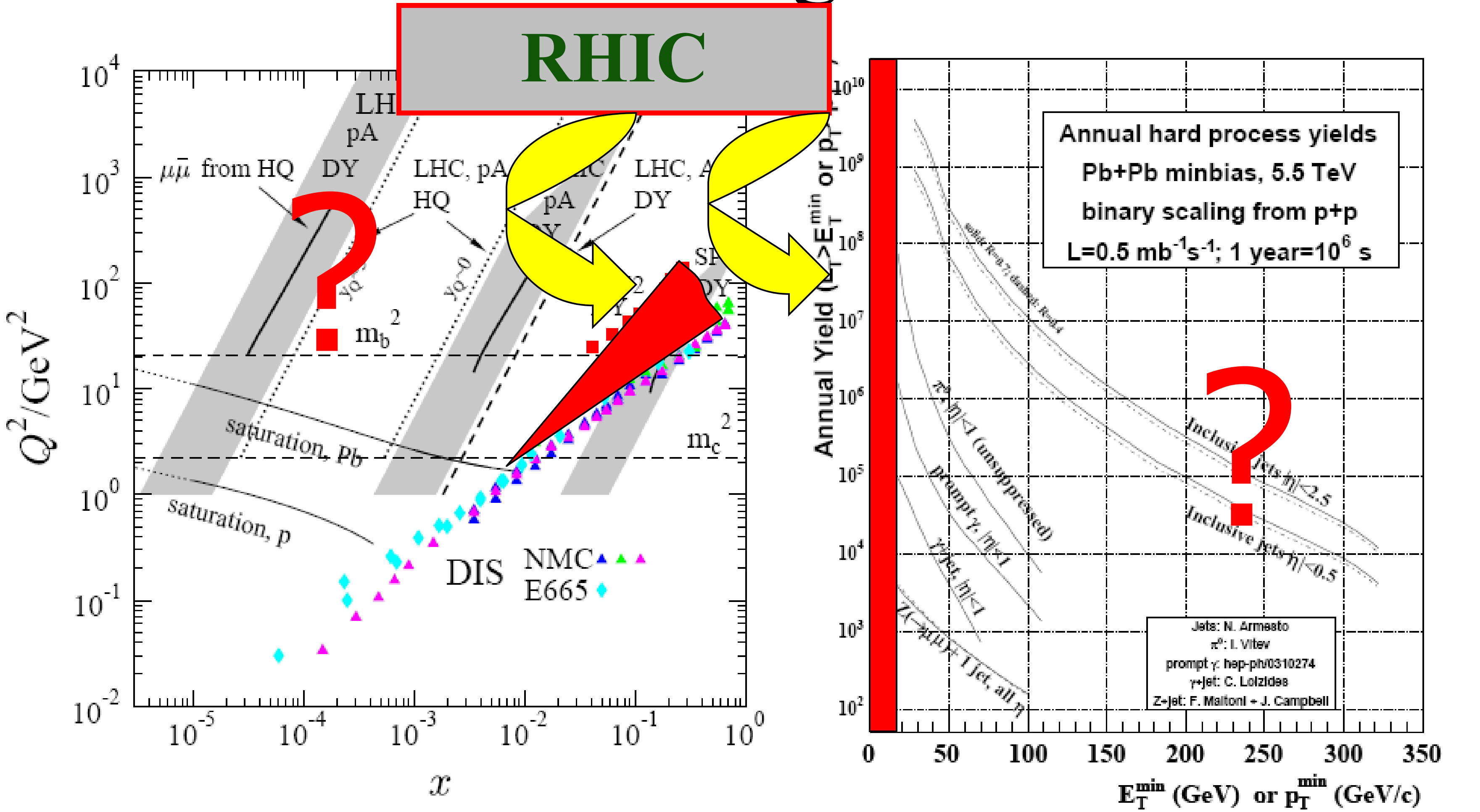
ALICE is a dedicate heavy ion experiment

CMS and ATLAS have own programs of heavy ion collisons

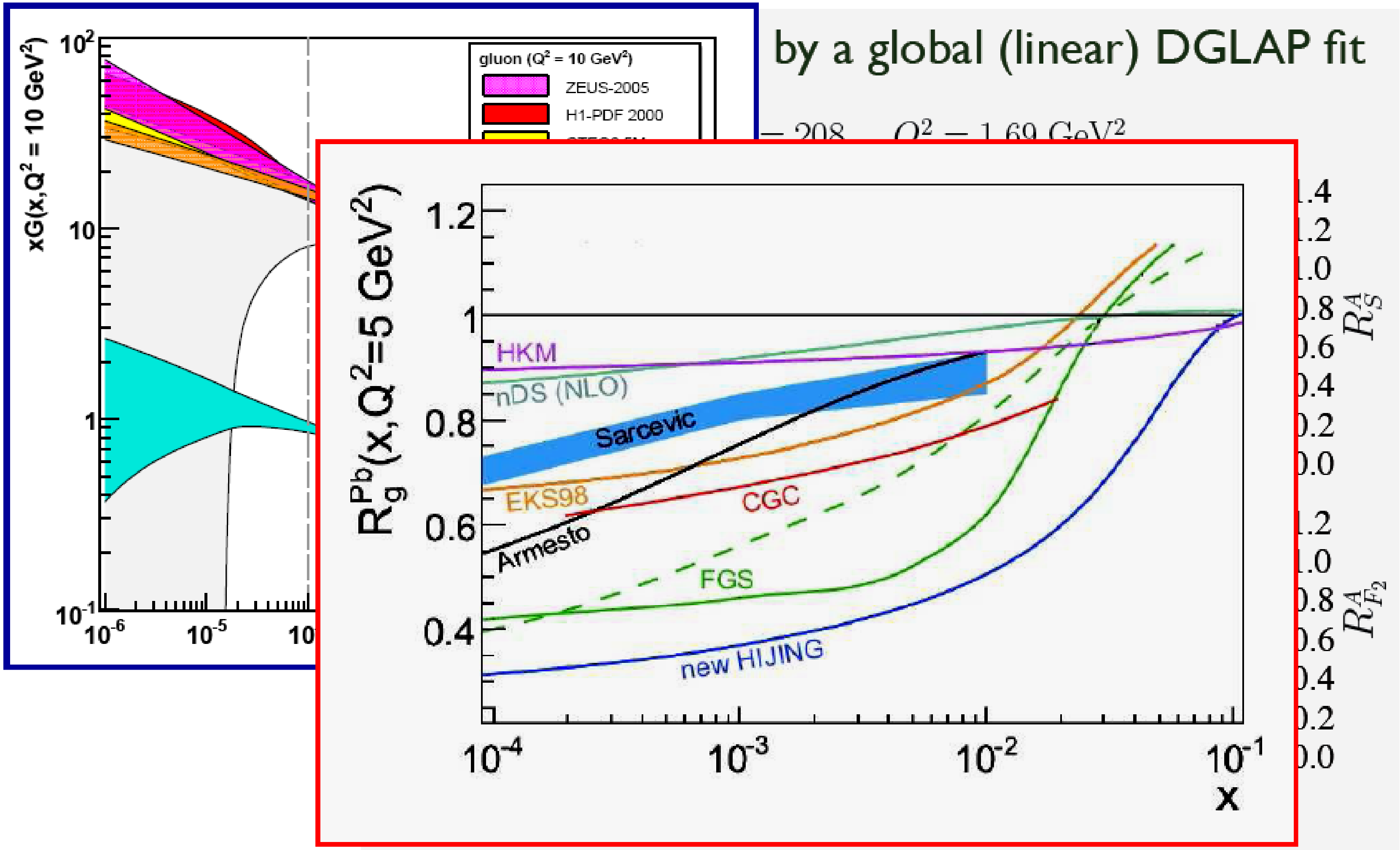
Specific question in heavy ion collisions:

- What is the initial state of the system and how is it produced ?
- What is the structure of the colliding objects ?
- What is the asymptotic limit of QCD ?

New regimes at the LHC



QCD at high densities - Modification of the PDFs



[Eskola, Kolhinen, Paukkunen, Salgado 2007]

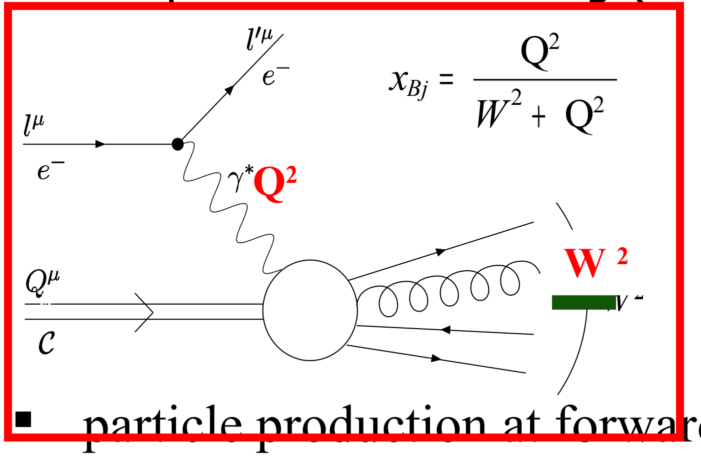
Applications of QCD at high energy

- Introduction: the saturation regime of QCD
  - weak coupling regime with high gluon densities
- Success of saturation
  - geometric scaling at HERA
  - high-rapidity suppression at RHIC
- Representative applications
  - Hadron multiplicities in AA collisions
  - Saturation physics at ultraperipheral heavy ion collisions
- Opportunities and open questions

When is saturation relevant ?

In processes that are sensitive to the small-x part of the hadron wavefunction

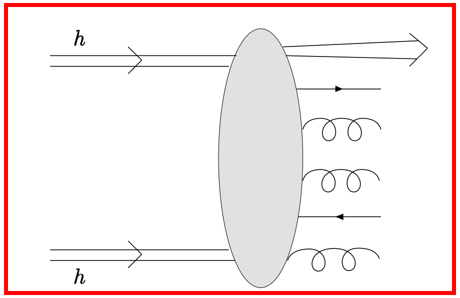
- Deep Inelastic Scattering (DIS) at small x_{Bj} :



in DIS small x corresponds to high energy

saturation relevant for inclusive, diffractive, exclusive events

- particle production at forward rapidities y :



$$x_1 \sqrt{s} = p_T\ e^{y}$$
$$x_2 \sqrt{s} = p_T\ e^{-y}$$

in particle production, small x corresponds to high energy and forward rapidities

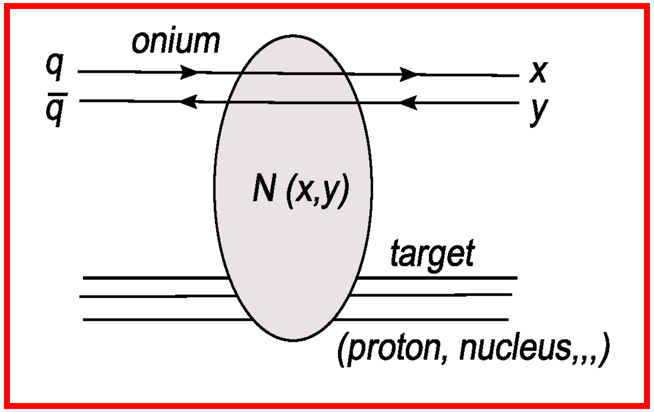
saturation relevant for the production of jets, pions, heavy flavours, dileptons

with HERA and RHIC: recent gain of interest for saturation physics

Nonlinear QCD evolution equations

➡ At high energies (or high densities) parton distributions (gluon) are solution of non-linear QCD evolution equations.

- An “evolution” equation, describing the change of the dipole scattering amplitude $N_Y(x,y)$ ~ gluon number under the change of scattering energy $\sqrt{s}$ ($Y \sim \ln s$: rapidity)



- Derived from QCD by using
  resummation w.r.t. $(a_s \ln s)^n$ & □
  strong gluonic field in the target

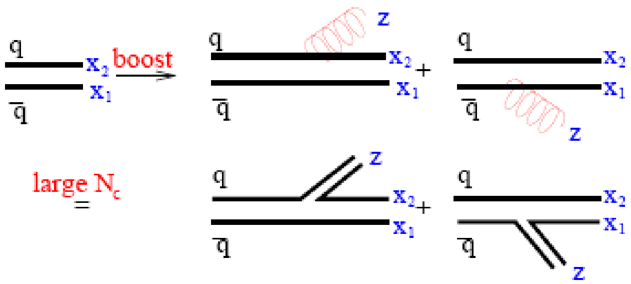
- A nonlinear differential equation, solved
  - numerically with/without impact parameter in coordinate/momentum space
  - analytically in some separate kinematical regimes

[Levin,Tuchin,Iancu,KI,McLerran,Mueller,Triantafyllopoulos,Kozlov]

The Balitsky-Kovchegov equation

[Balitsky 1996, Kovchegov 1999]

Rapidity evolution of the forward scattering amplitude of a $q\bar{q}$ dipole with transverse positions $\vec{x}_1$ and $\vec{x}_2$



$$\vec{r} = \vec{x}_1 - \vec{x}_2$$
$$\vec{r}_1 = \vec{x}_1 - \vec{z}$$
$$\vec{r}_2 = \vec{x}_2 - \vec{z}$$

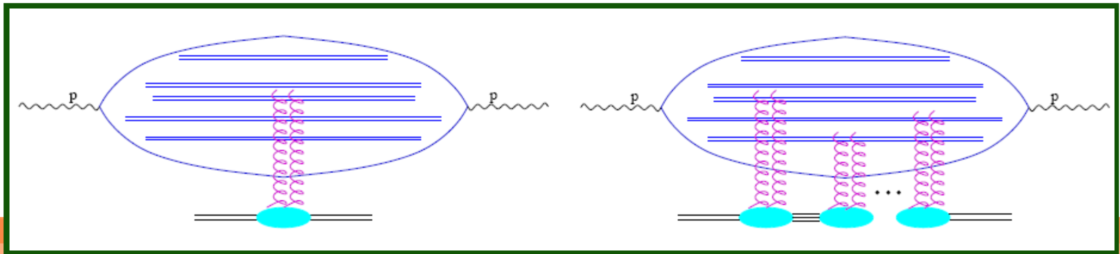
Non-linear term proportional to the square of N

$$\frac{\partial N(r,Y)}{\partial Y} =$$
$$= \int \frac{d^2z}{2\pi} K(\vec{r},\vec{r}_1,\vec{r}_2)\left[N(r_1,Y)+N(r_2,Y)-N(r,Y)-N(r_1,Y)N(r_2,Y)\right],$$

where the BFKL kernel is

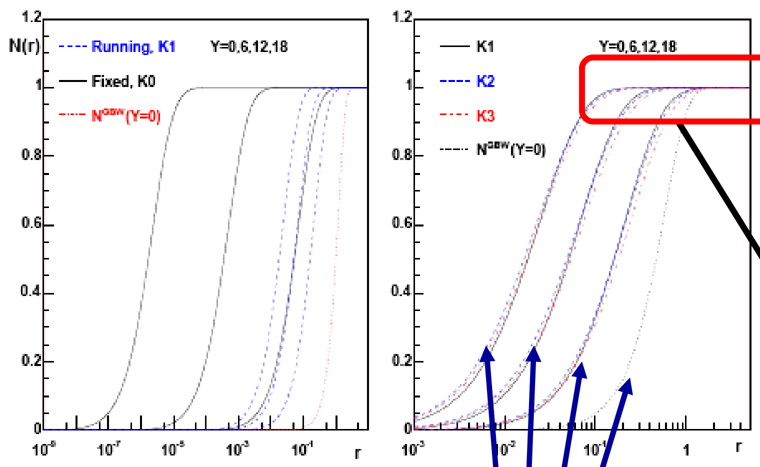
$$K(\vec{r},\vec{r}_1,\vec{r}_2) = \frac{\alpha_s N_c}{\pi}\,\frac{r^2}{r_1^2 r_2^2}$$

BFKL at LO. NLL corrections can be included



Looking at the numerical solutions

[Albacete, Armesto, Milhano, Salgado, Wiedemann 2004]



- ☑ Slower evolution for running coupling
- ☑ Almost independent of prescription

Numerical works: Gotsman, Levin, Lublinsky, Maor; Golec-Biernat, Motyka, Stasto; Armesto, Braun; Rummukainen, Weigert...

Saturation of dipole amplitude !

Evolution on rapidity Y

* See e.g. Javier Albacete et al. papers.

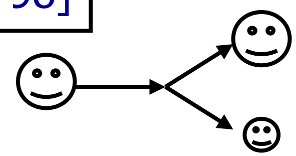
Intuitive analogy with dynamics of populations

Population dynamics

N(t) : (normalized) population density

When N<< 1 [Malthus 1798]

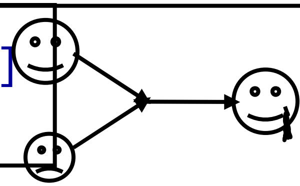
$$\frac{d}{dt}N(t) = \kappa N(t)$$



$\rightarrow$ $N(t) = N_0 e^{\kappa t}$ population explosion

When N~1 [Verhulst 1838]

The Logistic equation



$$\frac{d}{dt}N(t) = \kappa \left(N(t) - N(t)^2\right)$$

nonlinear

Exponential growth is tamed by the nonlinear term → saturation !

Initial condition dependence disappears at late time → universal !

Gluon dynamics

N_Y: gluon density

The BFKL Eq. ['75~]

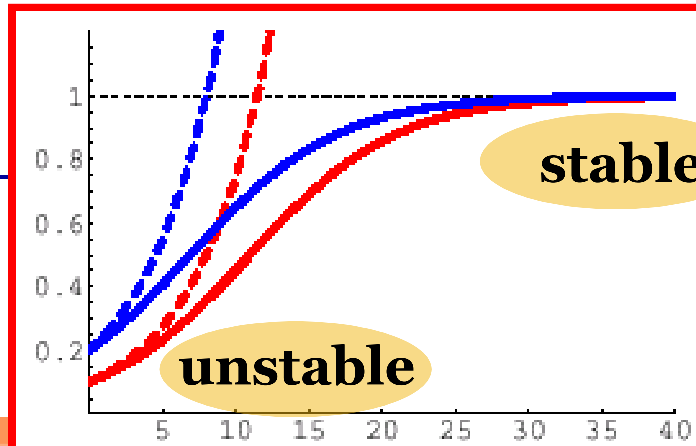
Multiple gluon emission

$$N_Y \propto \exp(\omega_P Y), \quad \omega_P = 4\bar{\alpha}_S \ln 2$$

unitarity violation

The BK Eq. ['99~]

Gluon recombination



Reaction-diffusion dynamics: saturation scale & geometric scaling

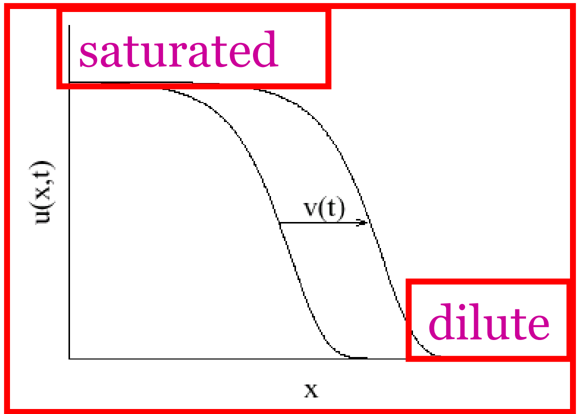
With a reasonable approximation, the BK equation in momentum space is rewritten as **the FKPP equation** (Fisher, Kolmogorov, Petrovsky, Piscounov), where $t \sim Y$, $x \sim \ln k^2$ and $u(t, x) \sim N_Y(k)$.

$$\partial_t u = \partial_x^2 u + u - u^2$$

Well-understood in non-equilibrium statistical physics including directed percolation, pattern formation, spreading of epidemics…(Traveling wave solution)

Fact 1: For a "traveling wave" solution, one can define the position of a "wave front" $x(t) = v(t)t$. → $x(t) \sim \ln Q_s^2(Y)$ Saturation scale !

- $1/Q_s(Y)$: transverse size of gluons when the transverse plane of a target is filled by gluons.
- "Boundary" btw dilute and saturated regimes
- Precise form of $Q_s(Y)$ determined



NLO BFKL : $Q_S^2(x) \propto (1/x)^\lambda = e^{\lambda Y}$, $\lambda \sim 0.3 \quad x = 10^{-2} - 10^{-4}$

Fact 2: At late time, the shape of a traveling wave is preserved, and the solution is only a function of $x - vt$. → $x - v(t)t \sim \ln k^2/Q_s^2(Y)$ geometric scaling

Applications to DIS at DESY-HERA

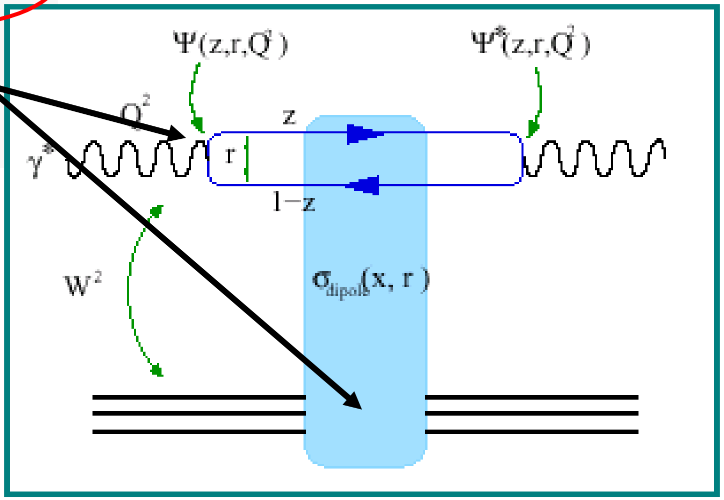
The simplest and cleanest process → precise information about saturation
No nuclear enhancement → need very small x to see saturation

DIS at small x : color dipole formalism

intuitively transparent formula for the total cross section and F_2

$$\sigma_{\rm tot}^{\gamma^* p}(x,Q^2) = \sum_{T,L}\int_0^1 dz \int d^2 r_\perp \left|\Psi_{T,L}(z,r_\perp,Q^2)\right|^2 \sigma_{\rm dipole}(x,r_\perp)$$

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{\rm EM}}\,\sigma_{\rm tot}^{\gamma^* p}(x,Q^2)$$



(i)LC wavefunction of a virtual photon (known)

(ii) Need the "dipole cross section" ←Effects of saturation

$$\sigma_{dipole}(x,r) = 2\int d^2b\, N_x(r,b)$$

Golec-Biernat & Wusthoff model ---- a simple parametrization
[Golec-Biernat,Wusthoff, Bartels, Kowalski,Teaney]

The CGC fit (based on solutions to the BK equation) [Iancu-Itakura-Munier, Soyez-Marquet, J.T.S. Amaral et al., etc.]

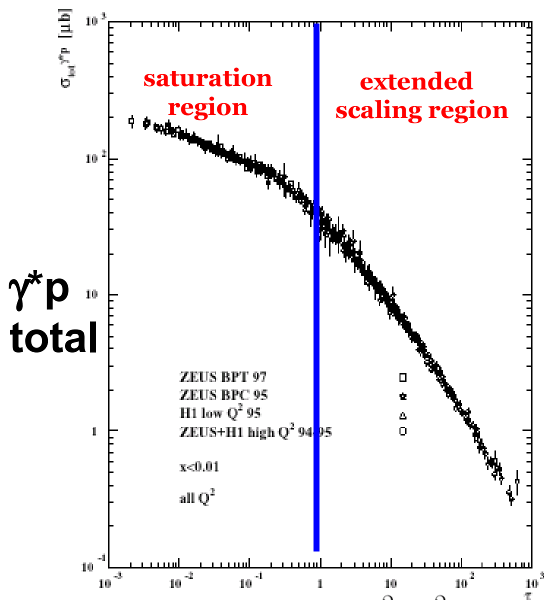
The geometric scaling of $\sigma_{DIS}(x, Q^2)$

$$N(r, Y) = N\left(r^2 Q_S^2(Y)\right) \Rightarrow \sigma_{DIS}(x,Q^2) = \sigma_{DIS}(\tau \equiv Q^2/Q_s^2(x))$$

$Q_s^2(Y) = Q_0^2\, e^{\lambda Y}$ this is seen in the data with $\lambda \approx 0.3$

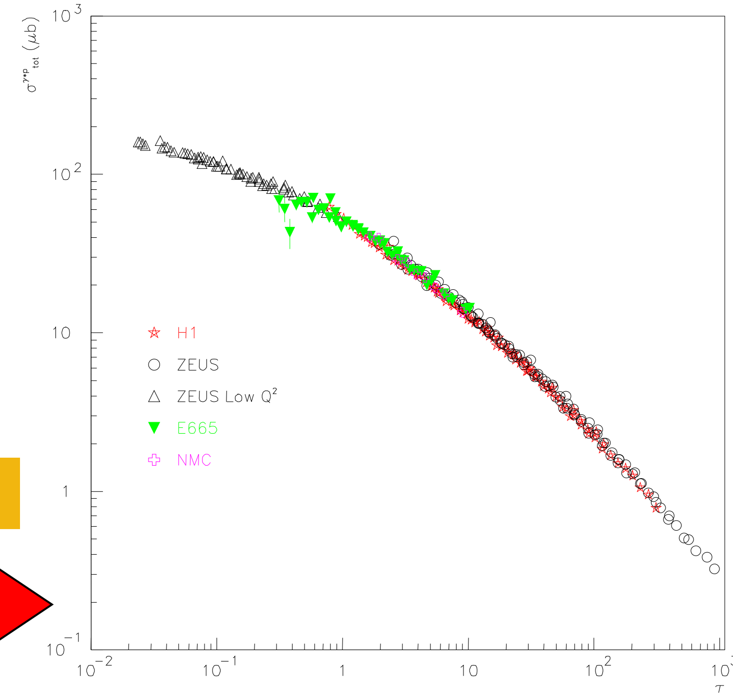
A. Stasto, K. Golec-Biernat and J. Kwiecinski, Phys. Rev. Lett. 86 (2001) 596

$x < 0.01, \quad 0.045 < Q^2 < 450\ \mathrm{GeV}^2$



Scaling variable $Q^2/Q_s^2(x)$

Recent test



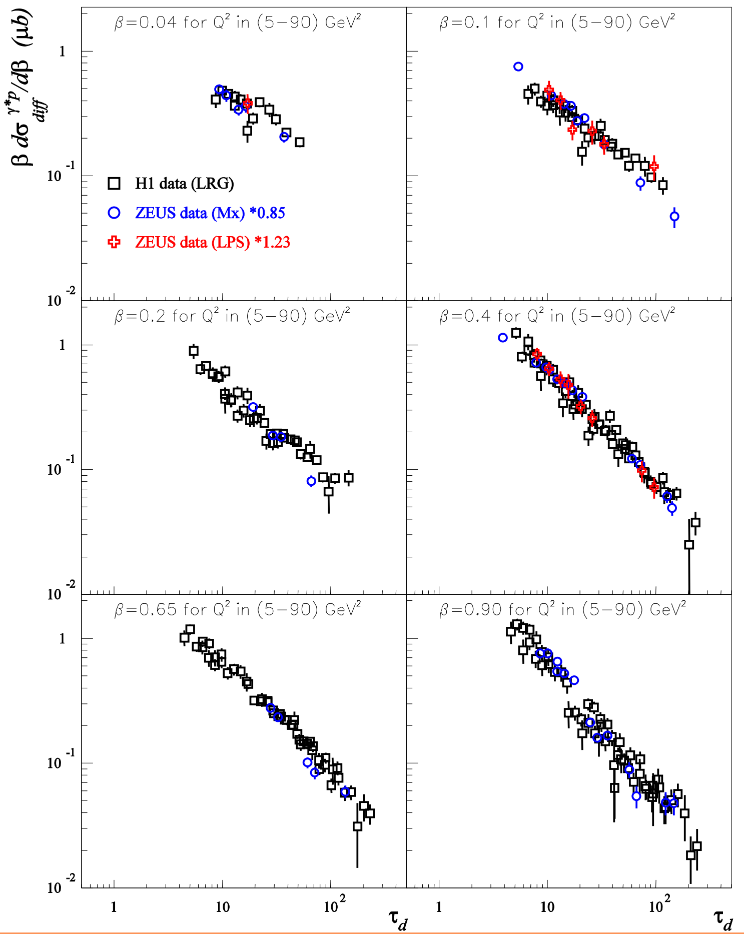
saturation models fit well F_2 data:

K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D59 (1999) 014017
J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D66 (2002) 014001
E. Iancu, K. Itakura and S. Munier, Phys. Lett. B590 (2004) 199
J.T. Santana do Amaral et al., arXiv:hep-ph/0612091
K. Golec Biernat and S. Sapeta, Phys.Rev. D74 (2006) 054032
A. Kormilitzin, arXiv:hep-ph /07072202

Geometric scaling in diffraction

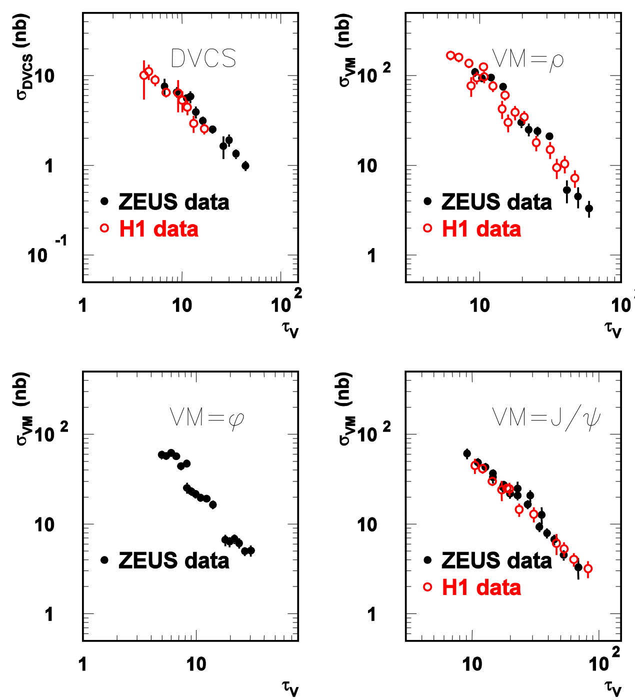
$$N(r, Y) = N\left(r^2 Q_S^2(Y)\right) \qquad \sigma_{DDIS}(\beta, x_{pom}, Q^2) = \sigma_{DDIS}(\beta, \tau_d \equiv Q^2/Q_s^2(x_{pom}))$$

C. Marquet and L. Schoeffel, Phys. Lett. B639 (2006) 471-477



scaling also for vector meson production :

$$\sigma_{VM}(x, Q^2) = \sigma_{VM}(\tau_V \equiv (Q^2 + M_V^2)/Q_s^2(x))$$



Saturation at HERA

Saturation predictions describe accurately a number of observables at HERA

- F_2^D

K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D60 (1999) 114023
J. Forshaw, R. Sandapen and G. Shaw, Phys. Lett. B594 (2004) 283
J. Forshaw, R. Sandapen and G. Shaw, JHEP 0611 (2006) 025

- Deeply virtual Compton scattering

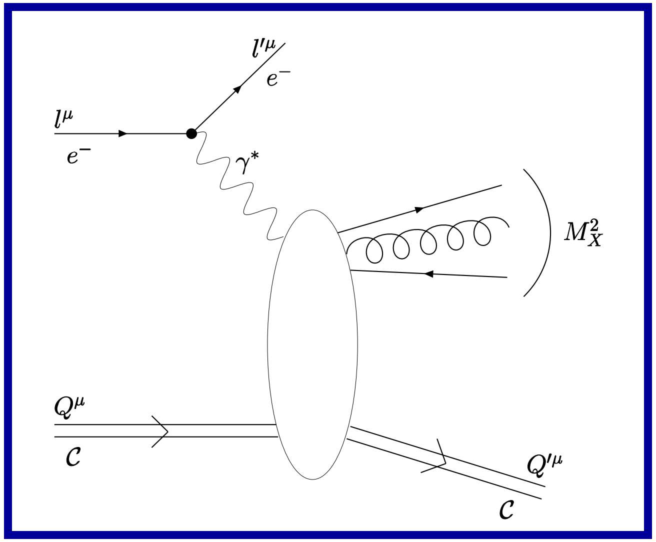
L. Favart and M. Machado, Eur. Phys. J C29 (2003) 365
L. Favart and M. Machado, Eur. Phys. J C34 (2004) 429

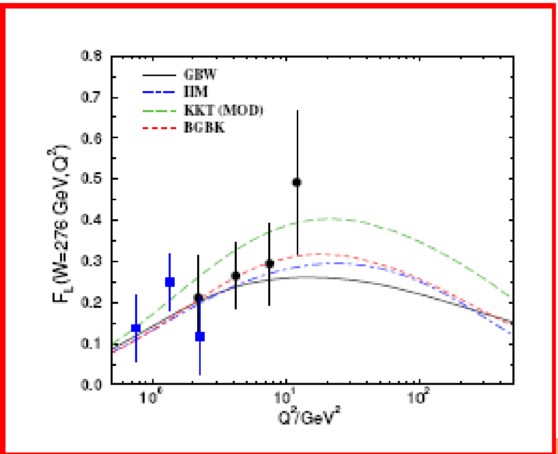
- Diffractive vector-meson production

S. Munier, A. Stasto and A. Mueller, Nucl. Phys. B603 (2001) 427
H. Kowalski and D. Teaney, Phys. Rev. D68 (2003) 114005
H. Kowalski and D. Teaney and G. Watt, Phys.Rev. D74 (2006) 074016
C. Marquet, R. Peschanski and G. Soyez, Phys. Rev. D 76, 034011 (2007)

- F_2^c, F_L

V. Goncalves and M. Machado, Phys. Rev. Lett. 91 (2003) 202002
M. Machado , Eur. Phys.J.C47 (2006) 365
G. Soyez, Phys.Lett.B 655 (2007) 32





Jumping (with relative success!) to AA collisions: the celebrated Kharzeev-Levin-Nardi model

- Formula for the inclusive production:

$$E\frac{d\sigma}{d^3p} = \frac{4\pi N_c}{N_c^2-1}\,\frac{1}{p_t^2}\;\times\int^{p_t} dk_t^2\,\alpha_s\;\varphi_{A_1}(x_1,k_t^2)\;\varphi_{A_2}(x_2,(\mathbf{p}-\mathbf{k})_t^2)$$

- Multiplicity distribution $\frac{dN}{dy} = \frac{1}{S}\int d^2p_t E\frac{d\sigma}{d^3p}$

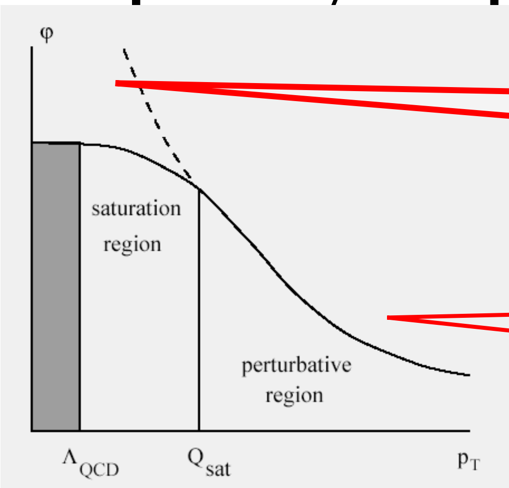
- S is the inelastic cross section for min.bias mult. (or a fraction corresponding to a specific centrality cut)

- Unintegrated gluon distribution function: $xG(x,Q^2) = \int^{Q^2} dk_t^2\,\varphi(x,k_t)$

$$\varphi_A(x,k_t^2) = \begin{cases} \kappa'\kappa\dfrac{S_A}{\alpha_s}(1-x)^4 & \text{for}\quad k_t < Q_s(x) \\ \kappa\dfrac{\alpha_s}{\pi}\dfrac{1}{k_t^2}(1-x)^4 & \text{for}\quad k_t > Q_s(x) \end{cases}$$

KLN ansatz for the unintegrated gluon pdf

Rapidity dependence in nuclear collisions



Saturation region: S_A/α_s

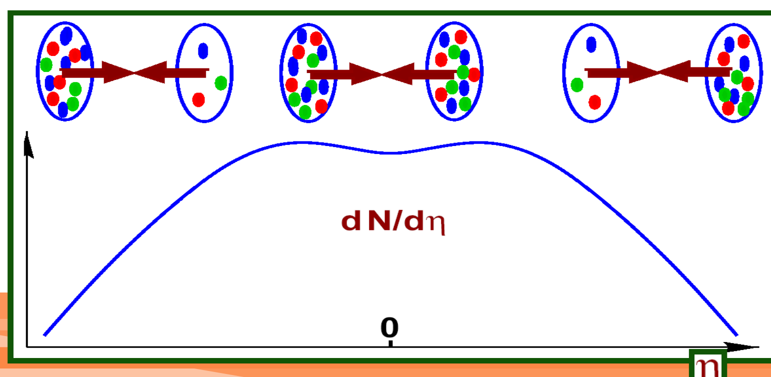
Perturbative region: α_s/p_T^2

- $x_{1,2}$=longitudinal fraction of momentum carried by parton of $A_{1,2}$
- At a given y there are, in general, two saturation scales:

$$Q_s^2(x_{1,2}) = Q_{s0}^2\left(\frac{x_{1,2}}{x_0}\right)^{-\lambda} = Q_{s0}^2\left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^{\frac{\lambda}{1+\lambda/2}} \exp\left\{\mp\frac{\lambda\, y}{1+\lambda/2}\right\}$$

$$x_1 = \frac{2Q}{\sqrt{s}}\,e^{-y}$$

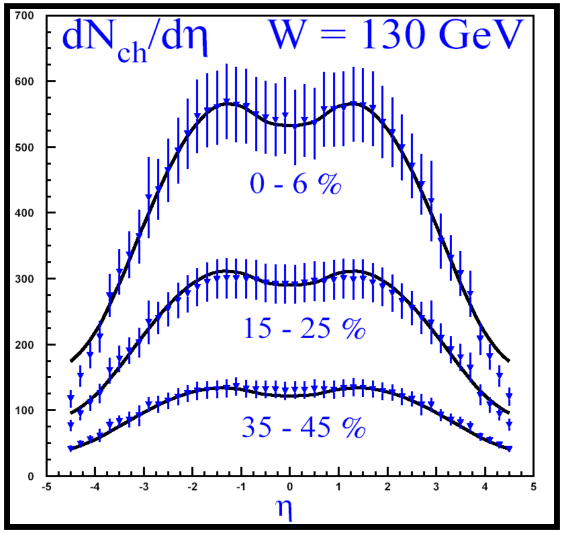
$$x_2 = \frac{2Q}{\sqrt{s}}\,e^{y}$$

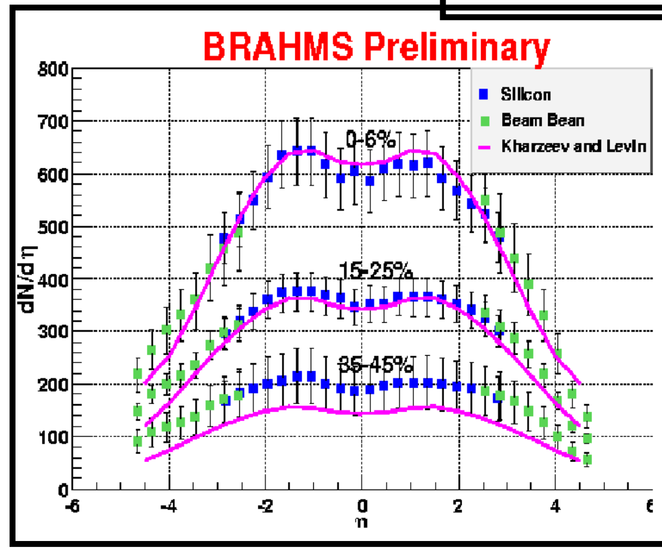


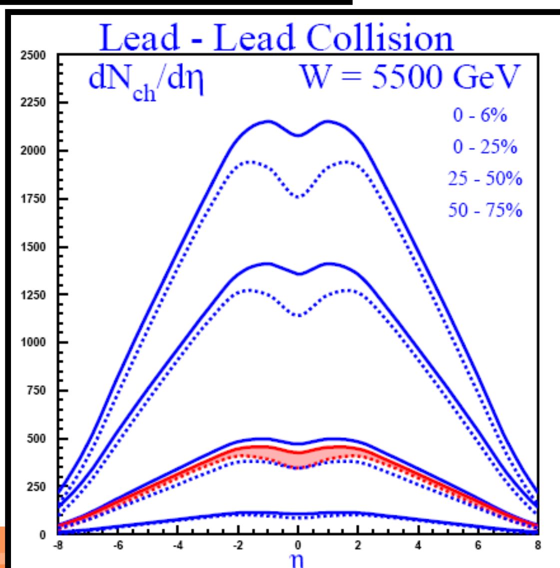
Results and predictions: rapidity dependence

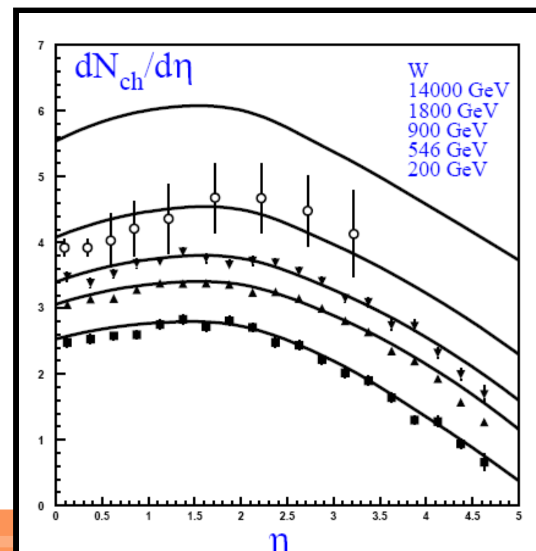
PHOBOS

W=200 GeV



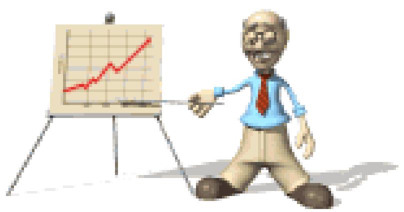


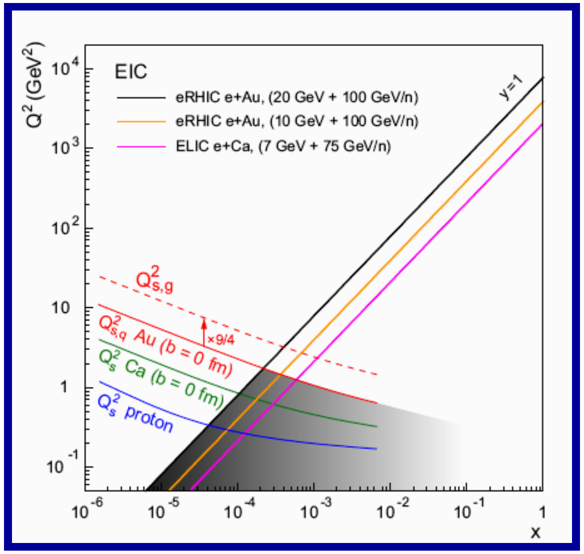




Main theory uncertainties at RHIC and LHC

- Saturation approaches are valid in a specific kinematical window. Matching is needed !
- Scattering amplitudes in general are known at LO level!
- Fragmentation funtions are not consistently used.



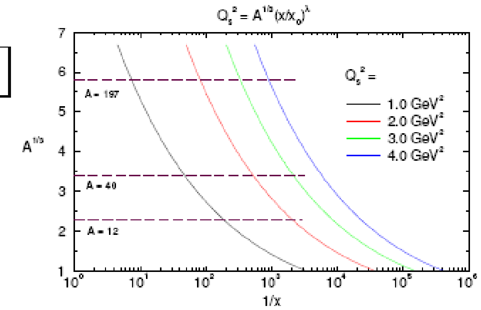


- Crucial point: considerable uncertainty on the Q_sat nuclear !
- Open questions about fluctuations contributions.

A gold mine: ultraperipheral AA colllisions

Saturation scale:

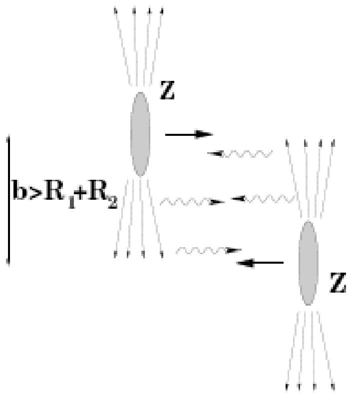
$$Q_s^2(x;A) = A^{\alpha} Q_s^2(x;p) = A^{\alpha} \times Q_0^2(\frac{x_0}{x})^{\lambda}$$



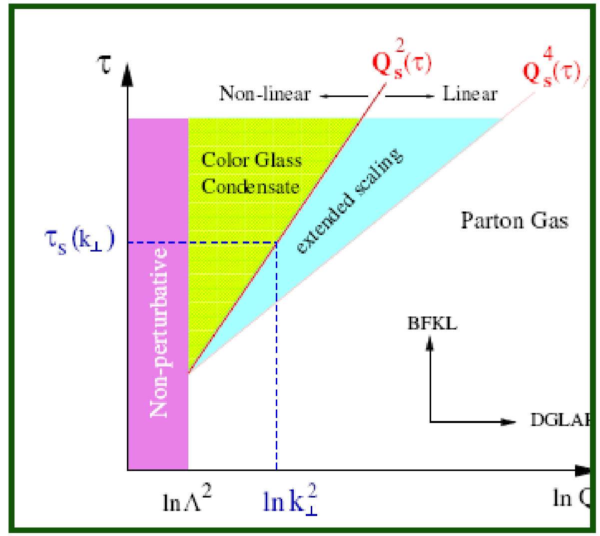
⇒ The nucleus amplifies the dynamical effects associated to the high parton density.

⇒ Saturation scale can grow up to $Q_s^2 \sim 5$ GeV^2 at LHC.

Photoproduction in pp (pA) or AA collisions:



- γp Processes:
  $\sigma(pp \to X) = n_p(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p})$
  $\sigma(pA \to X) = n_A(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p})$
- γA Processes: $\sigma(AA \to X) = n_A(\omega) \otimes \sigma^{\gamma A}(W_{\gamma A})$
- $\gamma\gamma$ Processes: $\sigma(AA \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma}(W_{\gamma\gamma})$



Main formulas

- The photoproduction cross section is given by,

$$\sigma(h_1 h_2 \to X)(\sqrt{s}) = \int \frac{d\omega}{\omega}\, n_h(\omega)\, \sigma_{\gamma h}\,(W_{\gamma h}^2 = 2\,\omega\sqrt{s})$$

- The number of equivalent photons:

where
collisi

$n_p\ (\omega$

where

Final state:

- In the inclusive heavy quark photon-hadron production the final state is characterized by one rapidity gap due to the dissociation of the hadron target.
- In contrast, in the vector meson production the final state is, in general, characterized by two rapidity gaps.

Center o

		AA		pA
A	$\sqrt{S_{NN}}$ (GeV)	$\mathcal{L}_{AA}$ ($cm^{-2}s^{-1}$)	$\sqrt{S_{NN}}$ (GeV)	$\mathcal{L}_{pA}$ ($cm^{-2}s^{-1}$)
		RHIC		
O	250	9.8×10^{28}	250	1.2×10^{30}
Si	250	4.4×10^{28}	250	8×10^{29}
I	208	2.7×10^{27}	208	2×10^{29}
Au	200	2×10^{26}	200	6×10^{28}
		LHC		
O	7000	1.6×10^{29}	9900	1.0×10^{31}
Ar	6300	4.3×10^{28}	9390	5.8×10^{30}
Pb	5500	4.2×10^{26}	8800	7.4×10^{29}

TABLE I. Luminosities and beam energies for AA and pA collisions at RHIC and LHC.

- Photoproduction can help us to gain information on the dynamics of γp and γA reactions for energies higher than HERA.

A simple example: vector mesons

- Photoproduction of vector mesons ($V = \rho, J/\Psi$):

$$\mathcal{I}m\,\mathcal{A}\,(\gamma h \to V h) = \int dz\, d^2\boldsymbol{r}\, \Psi^{\gamma}(z,r)\, \sigma_{dip}(\tilde{x},\boldsymbol{r})\, \Psi^{V*}(z,r)\,,$$

where $\Psi^{\gamma}_{n,\bar{n}}(z,\,\boldsymbol{r})$ and $\Psi^{V}_{n,\bar{n}}(z,\,\boldsymbol{r})$ are the light-cone wavefunctions of the photon and vector meson, respectively.

- Total cross section:

$$\sigma\,(\gamma h \to V h) = R_g^2 \frac{[\mathcal{I}m\,\mathcal{A}(s,\,t=0)]^2}{16\pi\, B_V}\,(1+\beta^2)$$

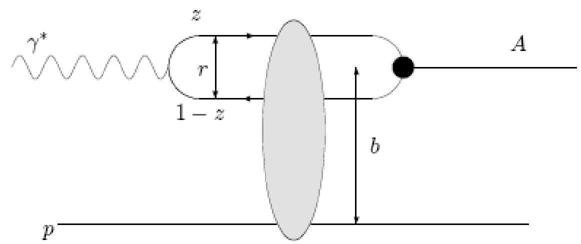
where β is the ratio of real to imaginary part of the amplitude and B_V labels the meson t-slope parameter.

- R_g is correction for skeweness (exclusive process).

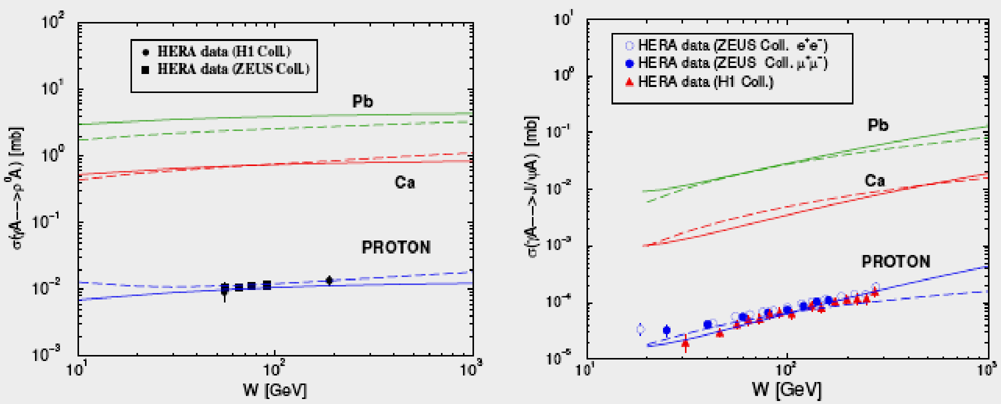
- The photonuclear cross section is written as

$$\sigma(\gamma A \to V\,A) = \left.\frac{d\sigma\,(\gamma A \to V\,A)}{dt}\right|_{t=0} \int_{t_{min}}^{\infty} dt\, |F(t)|^2$$

- $t_{min} = (m_V^2/4\omega)^2$.
- $F(t)$ is the nuclear form factor.
- The color dipole model allows to consider calculation of light d heavy meson in the same theoretical framework.



- Gonçalves, MVTM, Eur. Phys. J. C38 (2004).



Results for heavy ions and pp

Vector Meson Photoproduction in pA collisions

- Gonçalves, MVTM, **Phys.Rev.C73 (2006)**

$$\sigma(pA \to V\,pA) = \int \frac{dn_\gamma^A(\omega)}{d\omega}\,\sigma_{\gamma\,p\to V}(\omega)\,d\omega$$

- Integrated cross section (event rates/month) for the photoproduction of vector mesons in pA collisions at LHC:

	Vector Meson	**CGC model**
LHC	ρ	14 mb $(1 \cdot 10^{10})$
	J/Ψ	95 μb $(7 \cdot 10^{7})$

Vector Meson Photoproduction in pp collisions

- Gonçalves, MVTM **EPJC 40 (2005)** .
- Results consistent with J. Nystrand calculation.

$$\sigma(pp \to V\,pp) = 2\int \frac{dn_\gamma^p(\omega)}{d\omega}\,\sigma_{\gamma\,p\to V}(\omega)\,d\omega$$

$\sqrt{s} = 14$ TeV	$J/\Psi\,(3097)$	$\phi\,(1019)$	$\omega\,(782)$	$\rho\,(770)$
LHC	132 nb	980 nb	1.24 μb	9.75 μb

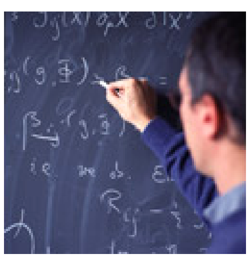
Vector Meson Photoproduction in AA collisions

- Gonçalves, MVTM, **EPJC 40 (2005)**

$$\sigma(AA \to V\,AA) = 2\int \frac{dn_\gamma^A(\omega)}{d\omega}\,\sigma_{\gamma\,A\to V}(\omega)\,d\omega$$

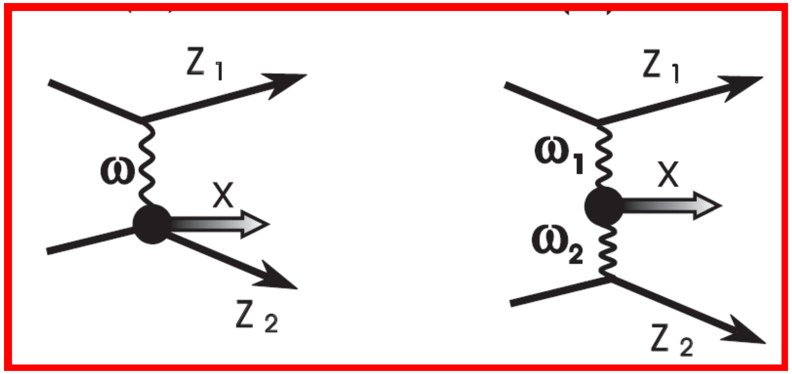
	HEAVY ION	$J/\Psi\,(3097)$	$\phi\,(1019)$	$\omega\,(782)$	$\rho\,(770)$
LHC	CaCa	436 μb	12 mb	14 mb	128 mb
	PbPb	41.5 mb	998 mb	1131 mb	10069 mb

$\Rightarrow$ The cross sections are large, mostly for light mesons at LHC energies.



Opportunities with UPCs at RHIC and LHC

- Several processes were still not considered, as direct photon, pseudo-scalar mesons (etas), glueballs, hadron production.
- Clean field for electroweak production (exotics, Higgs et al.)



→ RHIC (STAR) has measured meson photoproduction in UPCs.

- Tevatron is looking for Upsilon and Psi in pp coherent collisions.

→ ATLAS and CMS will look for UPC (dedicated task force).

- From theory side, the background for those processes have not been systematically computed !
- Clean field for Pomeron-Pomeron phenomenology.

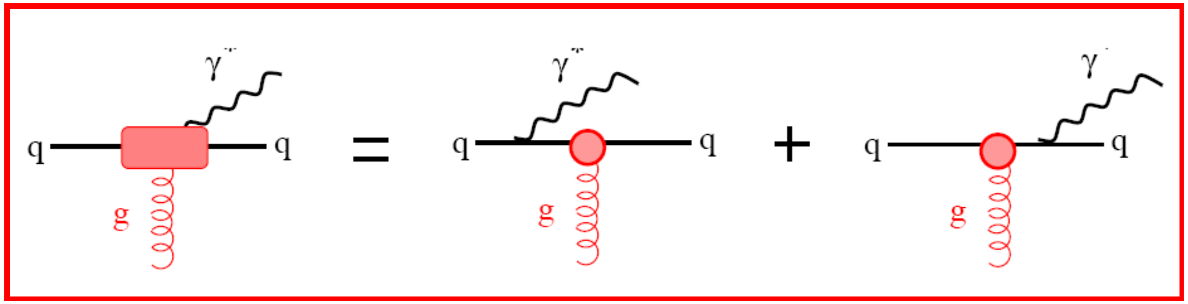
* See e.g. UPC Yellow Report, arXiv:0706.3356v2

List of opportunities at RHIC and LHC

Dilepton production

- To calculate hadron production one always needs to convolute quark and gluon production cross sections with the fragmentation functions. Since fragmentation functions are hard to calculate and are poorly known in general, they introduce a big theoretical uncertainty.

- Di-lepton production involves no fragmentation functions. It is, therefore, a much cleaner probe of the collision dynamics.



$$\frac{d\sigma_{inc}^{DY(L,T)}}{dx_1\,dM^2} = \frac{1}{M^2\,x_1}\,\frac{\alpha_{em}^2}{3\pi}\int_{x_1}^{1}\frac{d\alpha}{\alpha}\,F_2(x_1/\alpha)\int d^2r\,\left|\tilde{\Phi}^{L,T}(\vec{r},\alpha)\right|^2\sigma\left(\alpha r, x_2\right)$$

⇨Theoretical calculation for di-lepton production in dAu is pretty straightforward.

* See e.g. GFPAE papers on DY production and CGC physics

Heavy quark production

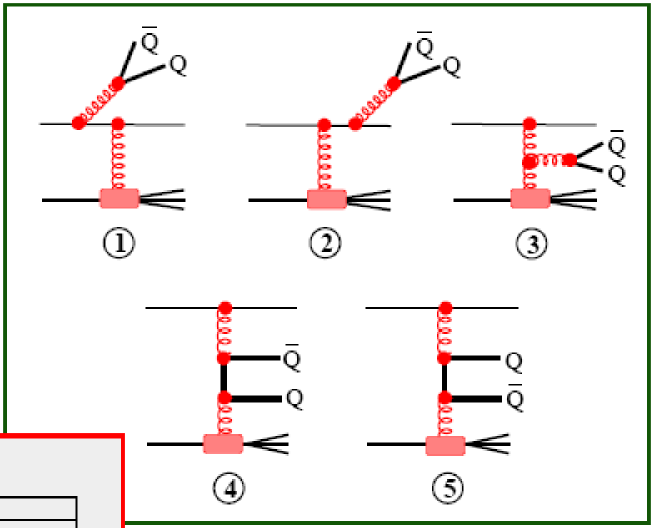
- Charm production is sentitive to saturation on gluon pdf and strong nuclear shadowing. Relatively simple final state signal.

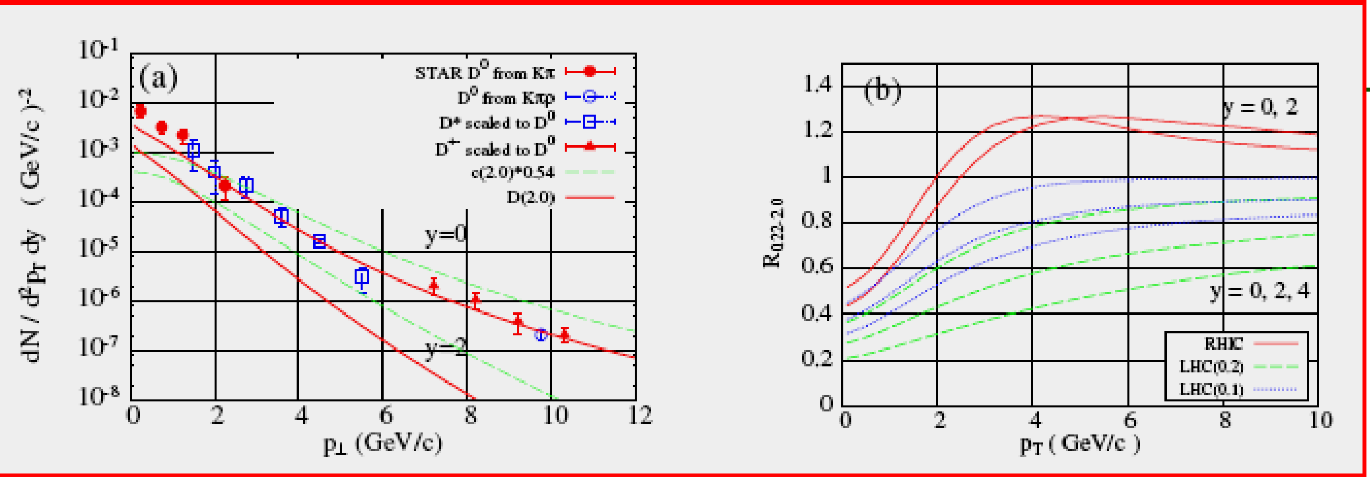
- HQs are a cleaner probe of gluon pdfs in pp and pA collisions.

$$\frac{d\sigma(pp\to\{Q\bar{Q}\}X)}{dy}=x_1G\left(x_1,\mu_F\right)\sigma(GN\to\{Q\bar{Q}\}X)$$

$$\sigma(GN\to\{Q\bar{Q}\}X)=\int_0^1 d\alpha\int d^2r\left|\Psi_{G\to Q\bar{Q}}(\alpha,r)\right|^2\sigma_{q\bar{q}G}(\alpha,r)$$

$$\sigma_{q\bar{q}G}(\alpha,r)=\frac{9}{8}\left[\sigma_{q\bar{q}}(\alpha r)+\sigma_{q\bar{q}}(\bar{\alpha}r)\right]-\frac{1}{8}\sigma_{q\bar{q}}(r)$$

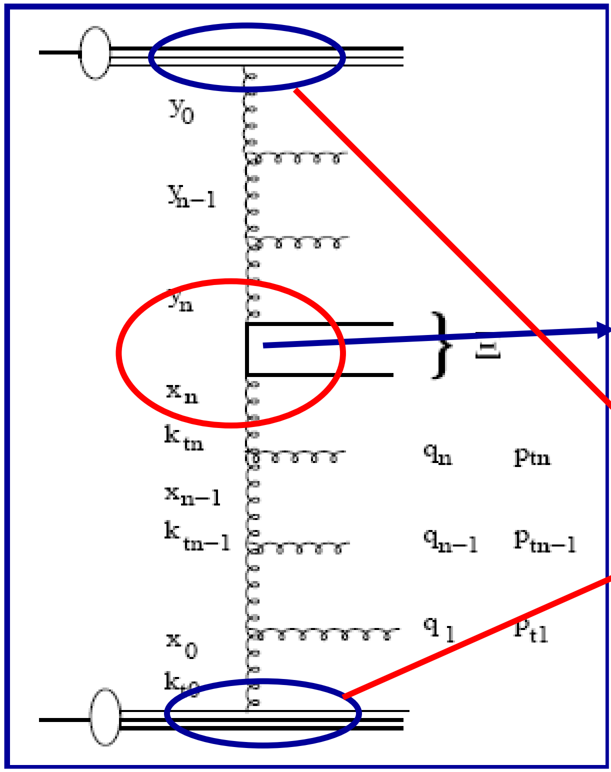




Quarkonium production

- Charm production is sentitive to saturation on gluon pdf and strong nuclear shadowing. Tests of initial and final state suppression.

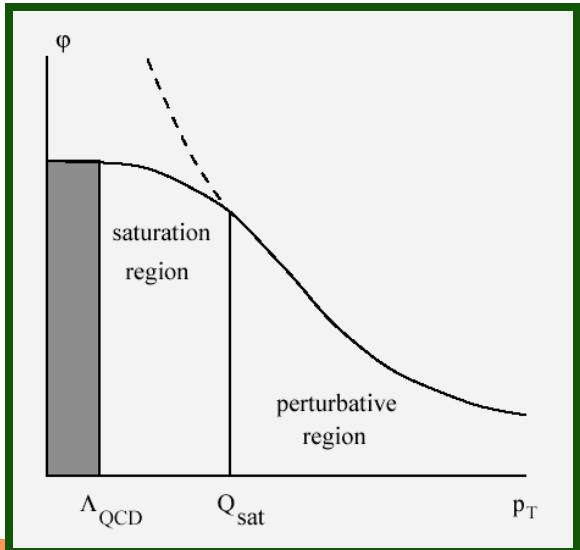
- Quarkonia are good probes of gluon pdfs in pp, pA and AA collisions.



$$\sigma^{KT}(pp \to J/\psi X) = \int \frac{dx_1}{x_1} \int d\vec{k}_{1T}^2 \int \frac{d\phi_1}{2\pi} \Phi(x_1, \vec{k}_{1T}^2, \mu^2) \int \frac{dx_2}{x_2} \int d\vec{k}_{2T}^2 \int \frac{d\phi_2}{2\pi} \Phi(x_2, \vec{k}_{2T}^2, \mu^2) \hat{\sigma}(g^* g^* \to J/\psi X, \hat{s}),$$

$$\hat{\sigma}(g^* g^* \to J/\psi X, \hat{s})$$

$$\Phi(x_1, \vec{k}_{1T}^2, \mu^2)$$

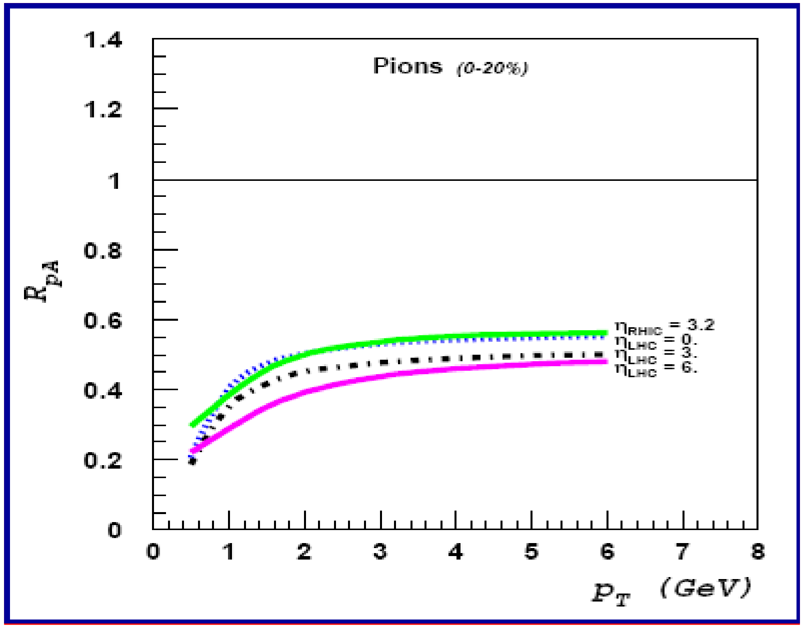


* See e.g. Baranov-Zotov-Saleev papers. Room available for new contributions!

Nuclear ratios in pA collisions

- In pA (or dA) collisions final state effects are expected to be smaller than in AA collisions. Good place to study initial state saturation.

- Nuclear ratios in pA are cleaner probes of nuclear gluon pdf.



$$R_{pA}(k,y) = \frac{\frac{d\sigma^h(pA)}{d^2k\,dy}}{A\,\frac{d\sigma^h(pp)}{d^2k\,dy}} = \frac{\frac{dN(pA)}{d^2k\,dy}}{N_{\text{coll}}\,\frac{dN(pp)}{d^2k\,dy}}$$

$$\frac{d\sigma^h}{d^2k\,dy} = \int \frac{dz}{z^2}\frac{d\sigma_G}{d^2k\,dy}(k/z)\,D_G(z,k)\,F(k/z,y) + \int \frac{dz}{z^2}\frac{d\sigma_Q}{d^2k}(k/z)\,xq_V(y,k/z)\,D_Q(z,k_T)\,F(k/z,y).$$

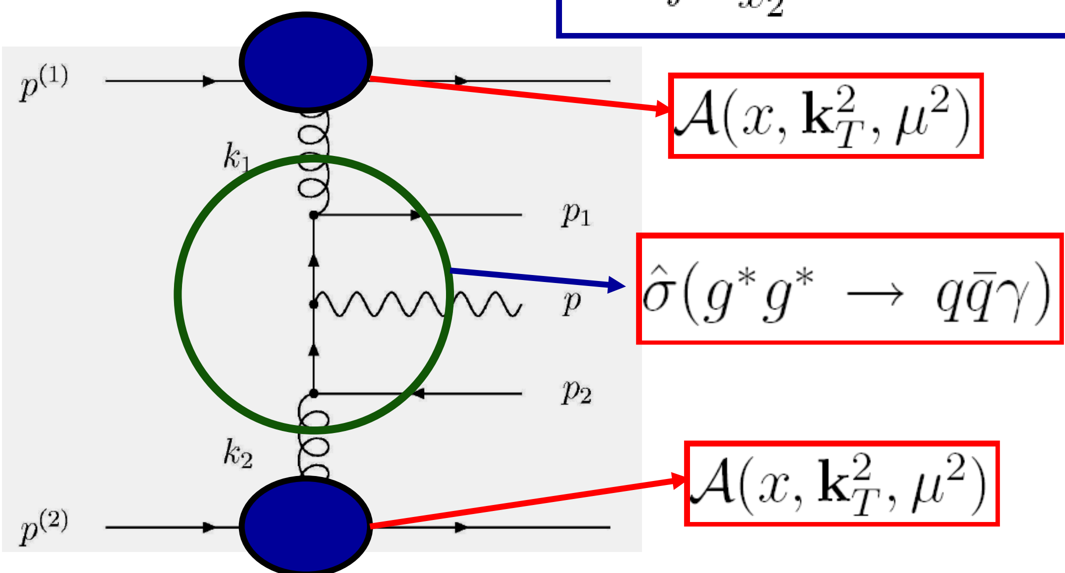
$$\frac{d\sigma_G}{d^2k\,dy} = \frac{\alpha_s C_F}{\pi^2}\frac{S_A}{k^2}\,x_p^{-\lambda}(1-x_p)^4\int_0^\infty dz_T\,J_0(k_T z_T)\,\ln\frac{1}{z_T\mu}\,\partial_{z_T}[z_T\,\partial_{z_T} N_G(z_T,y)]$$

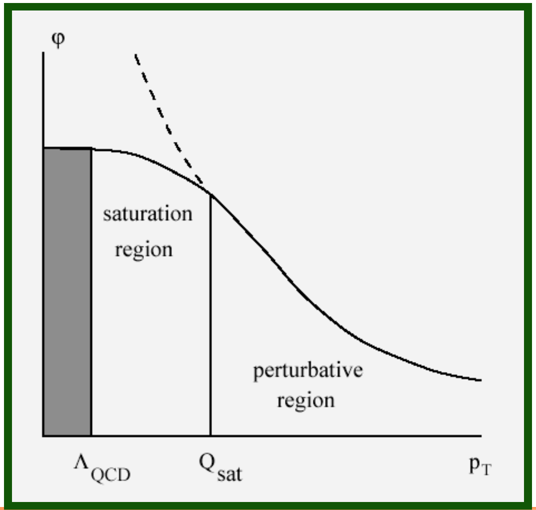
* See e.g. Kovchegov-Jalilian Marian papers, Raju-Tuchin works.

Prompt (direct) photons production

- The theoretical and experimental investigations of such processes have provided a direct probe of the hard subprocesses dynamics, since produced photons are largely insensitive to the effects of dinal-state hadronization.

$$\sigma(p\bar{p} \to \gamma X) = \sum_q \int \frac{dx_1}{x_1} \mathcal{A}(x_1, \mathbf{k}_{1T}^2, \mu^2) d\mathbf{k}_{1T}^2 \frac{d\phi_1}{2\pi} \times$$
$$\times \int \frac{dx_2}{x_2} \mathcal{A}(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{k}_{2T}^2 \frac{d\phi_2}{2\pi} d\hat{\sigma}(g^* g^* \to q\bar{q}\gamma),$$





* See e.g. Zotov-Baranov papers. See also Mariotto-Gonçalves papers.

Summary

- The LHC will prove QCD processes in a completely new energy and densities regime
- Parton distributions (main input in QCD calculations) are not completely constrained (or even unknown) in several processes to be measured at the LHC
- QCD at high densities (saturation approaches) could give a guidance in the extrapolation to these new regime
- RHIC has teach us some lessons to be used in future (hadron multiplicities, transverse momentum suppression at forward rapidities, centrality dependence)
- However, some questions arise concerning the QCD phenomenology:
  - Are there contributions in high energy QCD beyond the present knowledgement?
  - Are “dipoles” the correct degrees of freedom at high energies?
  - Do we have a consistent phenomenological picture ?

We will see at the RHIC II and LHC!